High-Performance Ultrafast Photodetectors

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FINAL REPORT

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1. Technical Objectives and General Approach

This project concentrates on the design, fabrication and characterization of compound semiconductor photodetectors in various material systems operating at near-IR wavelengths. We utilize resonant cavity enhanced (RCE)[1] detection scheme to optimize speed and responsivity of photodetectors. It is also desirable to combine multiple functions in a single photodetector structure. In addition to wavelength selectivity of RCE photodetectors, we have demonstrated that RCE detectors vertically integrated with one-pass detectors can be used for polarization sensing.
We have demonstrated RCE photodetectors working at 800-900 nm wavelength range with record bandwidth-efficiency products. In the following report we reference to the archival journal articles published under this funded program. The conference papers are listed at the end of the references.

2. RCE Schottky Photodiodes

Schottky photodiodes (PD) are very attractive for high-speed photodetection, since they have a simple material structure and fabrication thus allowing for easy integration with III-V discrete devices and integrated circuits. With the increasing demand for faster detector speeds, the optimized structure of a Schottky PD typically has a very thin absorption region. For front illuminated devices, a very thin Schottky metal is used so that light can penetrate the semi-transparent contact and reach the semiconductor. The resonant cavity enhanced (RCE) detection scheme is particularly attractive for Schottky type photodetectors since a semi-transparent contact can function also as the top reflector. RCE detectors with single-layer top mirrors are very desirable for post-growth adjustment of the resonant wavelength by simply recessing the top layer. We present theoretical and experimental results on spectral and high-speed properties of RCE Schottky photodiodes with semi-transparent top metal contacts.

We studied RCE Schottky diodes in GaAs/InGaAs material system operating at 900 nm wavelength (see Fig.1 for a schematic device structure)[2,3]. Similar principles apply to other III-V materials and different wavelength regions. The devices were grown on GaAs substrates by molecular beam epitaxy (MBE). The absorption layer is InGaAs with an In mole fraction less than 10 % and a thickness of 130 nm to eliminate the standing wave effect in the cavity. The position of the absorption layer in the depletion region is optimized to yield minimum transit time for electrons and holes. The resonant cavity is formed by a GaAs/AlAs DBR bottom reflector and the semi-transparent Au contact on top. After the Schottky metal, a top dielectric layer (Si_3N_4) is deposited. This matching layer is critical in the optimization of the optical responsivity. We consider only a single layer dielectric coating to maintain simple device fabrication.

We analyzed the dependence of responsivity on the thickness of the metal contact and the dielectric coating. By computer simulations, we demonstrated that these thicknesses can be optimized to yield nearly 75% quantum efficiency at resonance for this thin absorption region. Without a dielectric coating, the optimum Au thickness is about 150Å. For different dielectric top coatings (Si_3N_4) serving as impedance matching layers, the optimized Au layer thickness can cover a range from 150Å to over 300Å. The capability to use thicker Schottky metal reduces the spreading resistance..

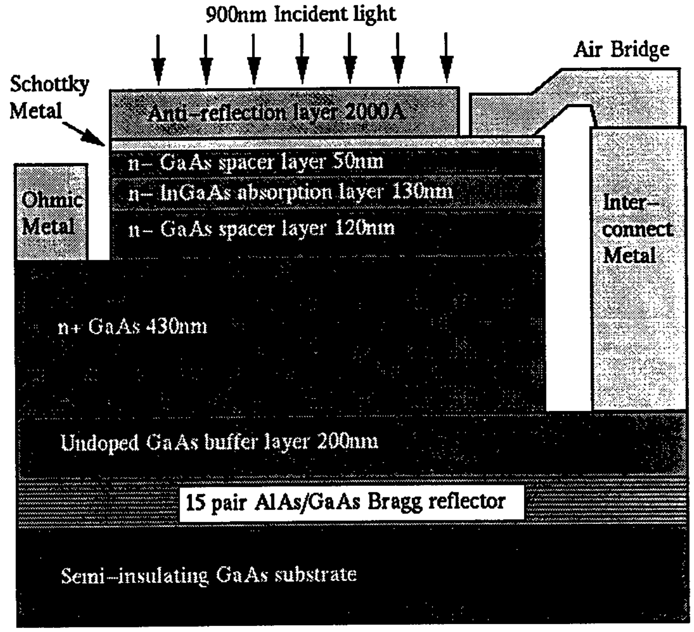

Fig. 1. Schematic layer structure of GaAs/InGaAs/AlAs RCE Schottky photodiode designed for 900 nm wavelength.

Photodiodes of various sizes were fabricated by standard photolithography with mesa isolation and a Au airbridge connecting the top contact to a co-planar transmission line. (See Figs. 2 and 3). The resulting devices showed breakdown voltages larger than 12 V. To emphasize the advantage of RCE detection, in Fig. 1, we also plot the quantum efficiencies of an optimized RCE Schottky PD and a conventional (one-pass) detector with identical absorption layer and metal

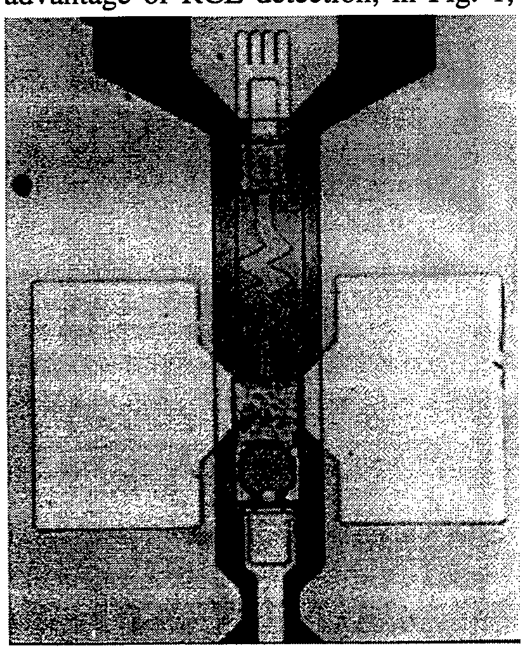

Fig. 2. Optical micrograph of typical RCE Schottky photodiodes fabricated using microwave co-planar transmission lines.

Fig. 3. Scanning Electron Microscopy picture of a RCE Schottky photodiode illustrating the air-bridge for top contact.

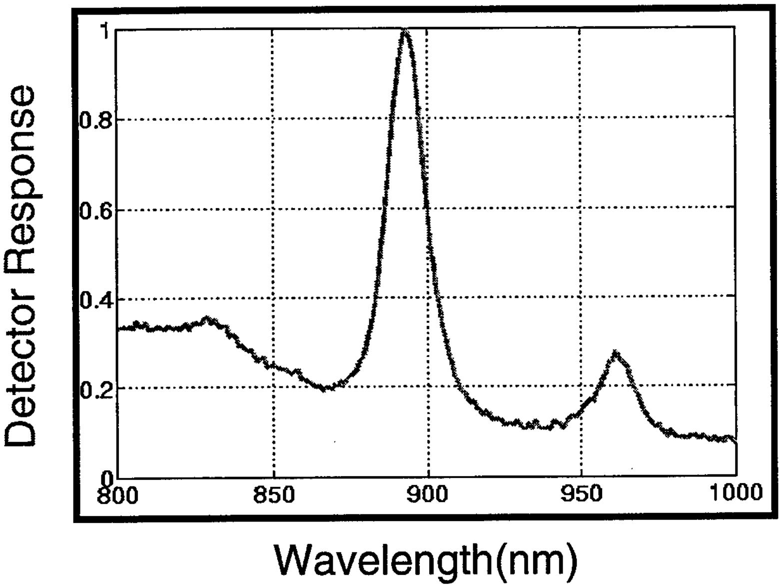

Fig. 4. Measured spectral response of RCE Schottky photodiodes. The detector response is normalized to unity. The peak efficiency is about 20%.

thickness. Figure 4 shows the measured photoresponse spectra of the devices. The peak quantum efficiency was measured to be 18% at 895 nm whereas the expected value was above 70%. Nevertheless, when compared with a single-pass device the enhancement factor is 6, and the FWHM is 15nm. On similar devices operating around 850 nm wavelength[4], where a more controlled experiment in terms of the Schottky metal thickness, and the absorption coefficient of the thin absorber was performed, efficiency values as high as 50% and a 25 GHz BWE were demonstrated.

High-speed measurements were performed using a picosecond mode-locked Ti:Sapphire laser. The devices were illuminated using a single mode fiber on a microwave probe station and the response at zero bias was observed with a 50 GHz sampling oscilloscope. For the wavelength dependence of the high-speed response, a 10x10 μm device was studied. Figure 5 shows the pulse response obtained at 895 nm, where the incident light is absorbed only in the thin InGaAs absorber with the exception of the Schottky metal, the rest of the cavity is nearly lossless, and the device functions as a RCE Schottky PD. The FWHM of the pulse response as measured on the scope is 10 ps. The measured rise time, which is a characteristic of the measurement setup was 9 ps. The pulse responses observed on the scope correspond to the total system bandwidth and are limited by the speed of the sampling scope. Considering a 9 ps FWHM pulse width for the scope, and a 1.2 ps laser pulse width, the estimated detector impulse width is 4.1 ps. This is a conservative estimate since the microwave components in the signal path and laser timing jitter also contribute to the measured pulse width. The corresponding 3-dB bandwidth is in excess of 100 GHz. Together with the 3 fold increase in efficiency the bandwidth-efficiency product of the devices is improved by a factor of 6 at resonance. We have also designed and fabricated top illuminated AlGaAs/GaAs RCE Schottky PDs demonstrating a peak

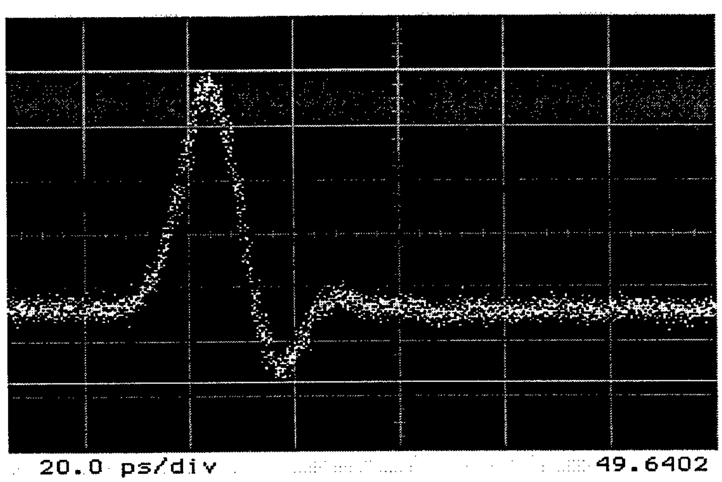

Fig. 5. Measured pulse response of RCE Schottky photodiodes.

quantum efficiency of η=50% and a 3-dB bandwidth of more than 50 GHz. The resulting BWE product is more than 25 GHz for operation wavelength in 800-850 nm wavelength region.[4] We have recently published a review of our results on design and optimization of high-speed RCE Schottky photodiodes. [5]

3. RCE pin Photodiodes

We also studied GaAs/AlGaAs based high-speed, high-efficiency, resonant cavity enhanced (RCE) p-i-n photodiodes.[6,7] Figure 5 shows a schematic representation of studied devices. Since the top surface is not metalized, one of the advantages of the p-i-n RCE photodetectors is that the quantum efficiency can be very high approaching unity. Also, by using a post-process recess-etch, we tuned the resonance wavelength from 835 nm to 795 nm while keeping the peak efficiencies above 90%.[6] Figure 6 shows the adjustment of the resonance wavelength by recessing the top surface.

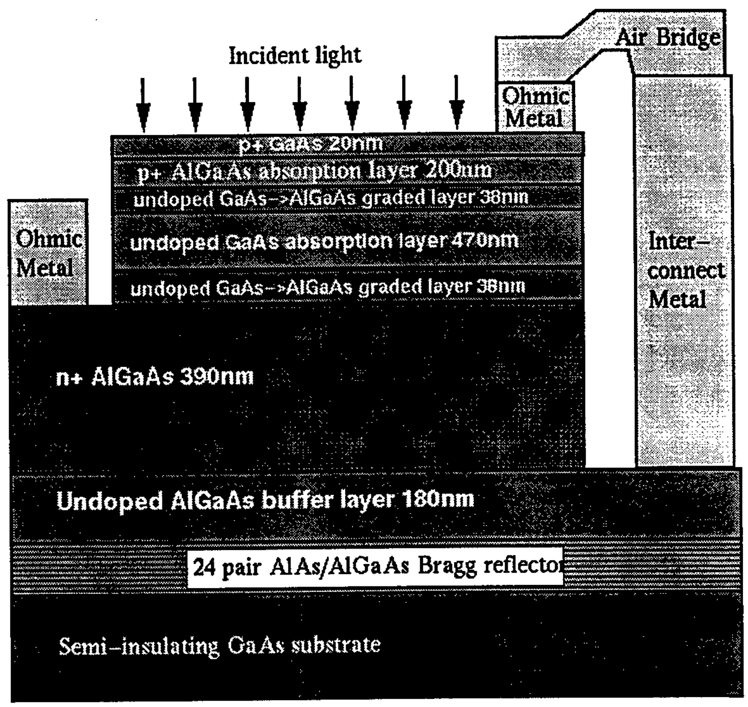

Fig. 5. Schematic layer structure of AlGaAs/GaAs/AlAs RCE p-i-n photodiode designed for 800-850 nm wavelength. range

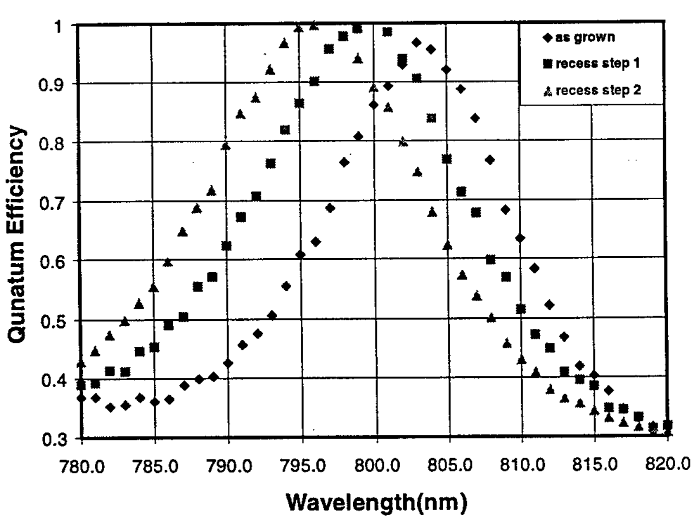

Fig. 6. Measured quantum efficiency of a near-unity efficiency GaAs/AlGaAs p-i-n PD for different recess etch steps.

The maximum measured quantum efficiency, was 100% with an experimental error margin of 2%.[7] The fabricated photodiode had an experimental setup limited temporal response of 12 ps. When the system response is deconvolved, the 3-dB bandwidth corresponds to 50 GHz, which is in good agreement with our theoretical calculations. Our work on high-speed photodiodes has been included in Optics in 1999 issue of Optics & Photonics News. [8]

4. RCE photodetectors with a flat resonant peak

The spectral response limits the suitability of the high performance RCE detectors in optical communications where the emitter wavelength tolerances are not very stringent and in short-pulse applications where the source has a broad spectral content. We theoretically studied structures for attaining a flat response at around the resonant wavelength.[9] Using computational tools, we examined the dependence of resonance condition on the magnitude and phase properties of the top mirror. In order to obtain a flat-top, we need a top mirror with a modified reflectivity with a dip in the reflectivity at the resonant wavelength. In Fig. 7, we plot the quantum efficiency of a detector with the modified top-mirror and a detector with no mirror structure on top exhibiting near-unity efficiency at resonance wavelength. A factor of 3 improvement in the width of the peak spectral response is evident in this graph at 90% of the peak efficiency.

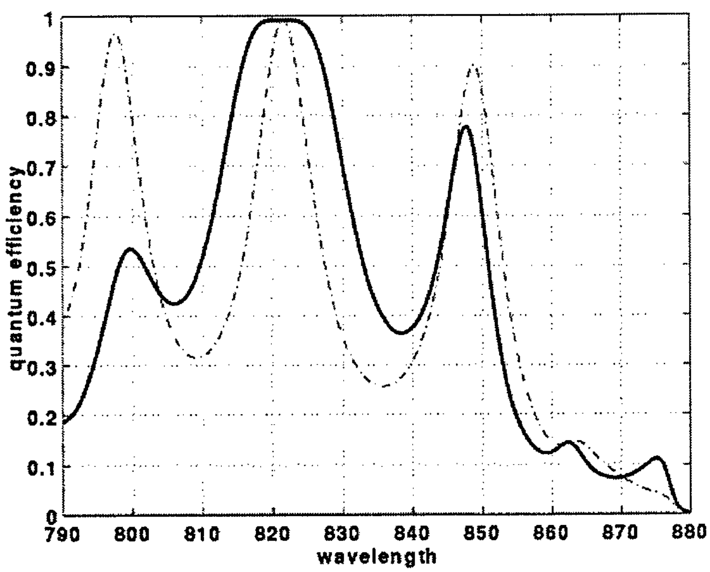

Fig. 7. The calculated quantum efficiencies of a near-unity efficiency RCE detector with (solid) and without (dashed) the modified top mirror

5. Vertical Cavity Polarization Detector Arrays for Polarization Imaging

A novel device architecture that detects not only light but also its polarization could substantially reduce the number of optical components in a range of systems. Image sensors built with the devices would represent an essentially new type of optical component. Sensitivity to polarization of light is similar to full-color imaging, where the eye can pick out details against a background based on color differences. A range of new applications may exist for a compact polarization imager, where the polarization of light reveals more information than humans can directly perceive.

The RCE detectors are inherently sensitive to polarization of light and such detector pairs can serve as polarization sensors.[10] The proposed device structure consists of a RCE photodiode vertically integrated with a conventional detector, creating a single device that is differentially polarization of light. The resulting vertical cavity polarization detector (VCPD) is constructed so that the top resonant cavity traps photons with a large electric vector normal to the surface while transmitting photons with a large normal magnetic vector to the bottom detector (Fig.8).[11] Thus, the combined detectors register a differential response depending on the polarization of the light striking the top surface.

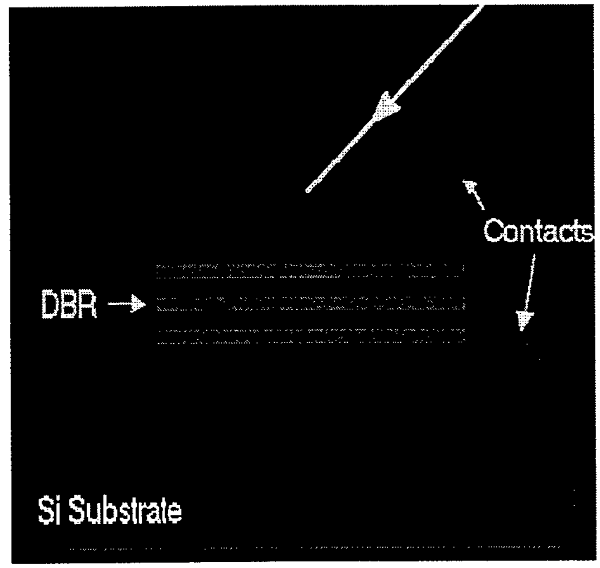

Fig. 8. Schematic representation of the proposed VCPD structure.

During the fabrication process, a Bragg reflector bottom mirror and reflection from the top silicon air interface form a resonant cavity photodiode. The bottom part of the structure is another Si detector fabricated with standard photolithography ion implantation and metalization processes. The big advantage to this kind of structure is that light is illuminating one mesa and alignment is not critical.

We considered Si for the specific application of magneto-optical drives the wavelength of light is about 650 nm. For that wavelength of light, the absorption coefficient of silicon is almost ideal for the application. We have

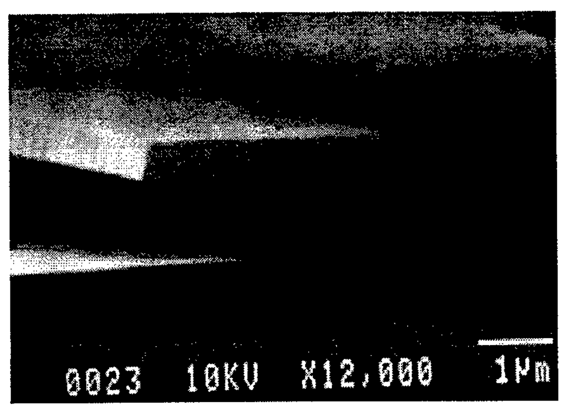

Fig.9. SEM photograph of a LPCVD grown $Si/SiO_2/Si_3N_4$ VCPD structure.

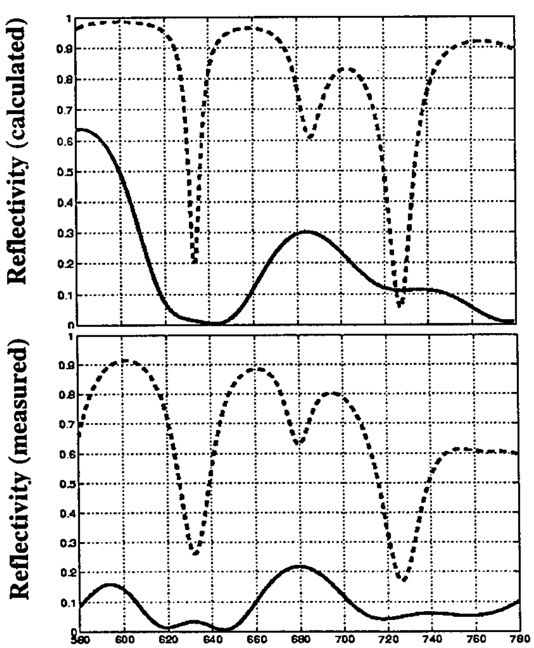

Fig.10. Theoretical (top) and measured (bottom) reflectivity of the VCPD structure of Fig.9.

fabricated Si VCPD structures using LPCVD for the growth of DBR and top Si detector layers (see Fig.9 for an SEM photograph of the fabricated structure).

Figure 10 shows the comparison of theoretical and measured reflectivities for the $Si/SiO_2/Si_3N_4$ VCPD designed for 632 nm wavelength demonstrating the feasibility of fabricating devices with prescribed optical properties. Due to the difficulties, mostly related to the inadequacy of the fabrication facility, we were unable to obtain the expected electrical performance of these devices.

6. Publications

In addition to the journal papers referenced in the discussion of the results above, we have recently submitted another article on light emission in Si APDs. [12] We have also published a number of conference papers. [13] Two students (Bora Onat and Olufemi Dosunmu) have received their MS degrees in EE, Bora Onat have completed his PhD in EE (now working at Lucent) and two other students (Gokkavas, EE and Ulu, Physics) are now in the final year of their PhD work.

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13. ABSTRACT (Maximum 200 words)

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14. SUBJECT TERMS
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